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Challenges and prospects for weed management in Pakistan: A review

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ABSTRACT

Weed management has become increasingly important in the backdrop of sustainable crop production, uncertain climatic patterns and food security concerns in Pakistan. Due to diverse agro-climatic conditions, 267 weed species have been identified to be responsible for causing monetary loss worth 3 billion USD annually. Weed competition for resources, interference with crops, weed-related increased incidence of pests and diseases in different crops, and high management costs incurred in controlling weeds make weed management a critical task for the farmers. Moreover, herbicide resistant weeds, labor shortage, higher wages, weed population shifts, changing climatic optima, unavailability of proper and timely inputs, ever increasing threats of invasive weeds, lack of knowledge and training regarding herbicides, and the poor financial resources of the small land holders are major hurdles towards effective weed management in Pakistan. These multi-dimensional problems need holistic line of action with multi-disciplinary collaboration. Improved knowledge of weed ecology, biology, genetics and molecular biology is essential for developing sustainable weed control practices. Some advances are already commercialized, and others are in the process of development. Advancements like vision guided machines for site-specific weed management, recognition and application modules, development of air inclusion nozzles, nanoherbicides, water based formulations with fewer hydrocarbons, herbicide-resistant transgenic crops, robotics to monitor and spray weeds, decision support systems and predictive modeling can be adopted to foster modern weed management in the country. Various conventional weed management approaches like narrow row spacing, row orientation, increased crop density, use of cover crops, intercropping, development of weed-competitive crop cultivars, and their integration can help reduce herbicide input under a given scenario. There is dire need to establish regional weed research institutes under various cropping systems to carry out strategic and applied research in weed science. Innovative teaching and training practices are needed to tackle complex weed management challenges. Effective linkages between academia-research-industry-extension services could play a pivotal role to reframe technological advancements and legislation and to advocate innovations to the farmers. Capacity building, more research fund allocation, and reorienting educational system seem indispensable. Here, we have presented a broad review to summarize the current state of knowledge about the problems and prospects of sustainable weed management approaches in Pakistan. Advanced weed management approaches keeping in view the local agro-ecological conditions have also been discussed in this review to improve the scientific knowledge so that the discipline gets stronger and more focused than ever before.

1. Introduction

Pakistan is 6th most populous country in the world. The population of Pakistan is expected to reach 350 million by 2050 (United Nations, 2012; Ministry of Climate Change, 2012; Planning Commission, 2014). This situation is likely to cause serious food security concerns as more than half of the country's population is already classified as food insecure (IFPRI's food security portal at http://www.foodsecurityportal.org/pakistan). More food must be produced to meet the ever-increasing demands of the burgeoning population, and maintain

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food security in Pakistan (Kirby et al., 2017). This situation calls for increased crop production beyond the current level that will impose immense pressure on already dwindling natural resource base (Ali et al., 2017a; Hanif et al., 2017). Among the major biological constraints limiting crop productivity and sustainability in Pakistan, weed infestation remains the most devastating one (Khaliq et al., 2013; Areeb et al., 2016). Weeds are the most omnipresent class of all crop pests, infesting the fields year after year. Weeds represent multidimensional problems in each and every cropping system, the most significant of which is a loss of quantity and quality of final produce (Ashiq and Aslam, 2014). Being a botanical pest, weeds share similar trophic level as that of crop plants, and weed-crop competition results in a substantial crop yield loss (Ali et al., 2015b; Javaid et al., 2016; Ramesh et al., 2017). The cost incurred in controlling weeds is exclusive of this loss. Weed-inflicted yield losses in Pakistan have been estimated up to 36 million tons, the monetary value of which is about 3 billion US$ annually (Mushtaq and Cheema, 2007; Marwat et al., 2008; Zaffar et al., 2010) and is much higher than damages caused by insect pests and pathogens (Naseer-ud-din et al., 2011). Almost 267 plant species have been identified as weeds in Pakistan. Out of these, approximately 160 have been reported as weeds in Punjab; of which 50 are serious weeds causing major economic losses in major field crops (Ashiq and Aslam, 2014). Weed related yield losses in important crops of Pakistan are shown in Fig. 1. Optimum weed free period required for satisfactory yield and range of weed related yield reductions and monetary losses in field crops of Punjab province (where major area and production of these crops is found) are presented in Table 1. The reasons for these losses include weed-crop competition, high weed management costs, and interference of weeds with crop management practices (Abbas et al., 2006; Ali et al., 2015a, 2015b, 2017). Further negative impacts of weeds are faced during harvesting, marketing, and storage. In addition, weeds increased the incidence of pests and diseases in different crops and also endanger irrigation system.

To secure the future food security, safeguard the crop production and to bridge the existing yield gaps, weed management has become more imperative than ever before for sustainable crop production in Pakistan (Marwat et al., 2008; Mahmood et al., 2013; Matloob et al., 2015a,b). While many growers in developed countries are integrating a balanced combination of diverse weed management approaches, integrated weed management (IWM) is still at its infant stage as compared to integrated pest management (IPM). Labor shortages, higher wages, weed population shifts, changing climatic optima, unavailability of proper and timely inputs, ever increasing threats of invasive weeds, lack of knowledge and training regarding herbicides, and the financial resources by the farmers are major hurdles for the effective and timely weed management in Pakistan (Khaliq et al., 2011, 2013b; Ali et al., 2015a, 2015b; 2017a). In addition to this, injudicious use of herbicides has resulted in the evolution of resistant weed biotypes, and crop phytotoxicity with harmful implications for ecosystem and human health (Marwat et al., 2011; Ali et al., 2013b; Abbas et al., 2015; 2016, 2017), which needs further attention of the researchers.

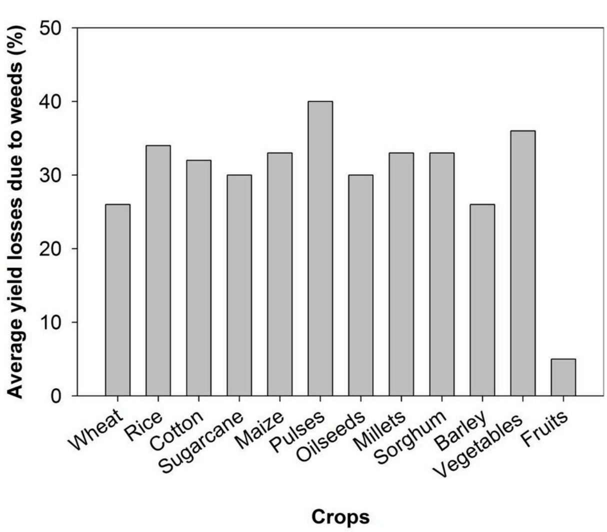

Fig. 1. National average yield losses due to weeds in important crops of Pakistan (Ashiq and Ata, 2005).

Table 1
Optimum weed free period requirements, range of weed related yield and monetary losses in Punjab-Pakistan.

Crop	Optimum weed free period required (weeks after sowing)	Range of weed related yield losses (%)	Monetary value (Million US$)
Maize	5–6	24–47	22.65–44.39
Rice	4–6	17–39	58.89–136.81
Wheat	8–10	18–30	257.30–432.16
Cotton	6–8	13–41	96.94–302.60
Sugarcane	8–10	10–35	43.49–154.02
Oilseeds	6–8	21–45	21.74–47.11
Pulses	4–6	25–55	51.64–114.16
Vegetables	First 1/3rd growing period	39–89	86.07–196.60

Modified after Ashiq and Aslam (2014).

Various weed management approaches are used to combat weed menace to increase the crop productivity and profitability in different agro-ecological regions of Pakistan (Khaliq et al., 2013; Siddiqi et al., 2014). A better understanding of weed ecology and biology, improved cultural practices like narrow row spacing, row orientation, increased crop density, use of cover crops, intercropping, development of weed-competitive crop cultivars, and their integration can help the conventional weed management (Ali et al., 2013a, 2017a; Abbas et al., 2017; Tanveer et al., 2017; Hanif et al., 2017). Advanced weed management techniques are needed for effective weed management in Pakistan. These may include targeted and site-specific weed control, variable rate application of soil applied herbicides (especially when weed growth is patchy, and spatial variability exists for seed bank and soil properties), harvest weed seed collector, weed seed destruction through predation and microbial decay, nano-herbicides and optical spraying technologies. Implementing the quarantine measures and legislation will assist in preventing the invasion of alien plant species, and improving the efficacy of existing weed management practices (Rashid et al., 2014; Nasim and Shabbir, 2012; Bajwa et al., 2016).

The primary objective of this review is to highlight the neglected or least studied domains of weed science and discuss potential challenges and existing knowledge gaps in weed management together with future prospects for weed science in Pakistan. Advanced approaches to manage weeds keeping in view the local agro-ecological conditions have also been discussed. The purpose of this review is to improve researcher's perceptions about the use of modern weed control methodologies to combat ever increasing weed management challenges in Pakistani agriculture.

2. Weed related issues in Pakistan

2.1. Herbicide resistance

In recent past, herbicide resistance has emerged as the greatest concern of contemporary agriculture which relies primarily on herbicides as sole mean of weed control. Focused work on herbicide resistance remained a neglected domain of weed research in Pakistan. The Pakistani weed scientists largely ignored the case studies depicting the evolution of isoproturon resistant *Phalaris minor* Retz. in Indian Punjab (Malik and Singh, 1995) with similar agro-ecological conditions and management scenarios as in Pakistani Punjab. The selection pressure exerted by herbicide/s with a similar mode of action was conducive to adaptive mechanisms within weed population favoring resistance

evolution. Use of herbicides with a single mode of action over a prolonged period has led to the evolution of herbicide resistance in important weed species like barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], Canada thistle (*Cirsium arvense* L.), and littleseed canarygrass (*P. minor*; Heap, 2017) across the globe. In Pakistan, tolerance of aerobic rice weeds like crowfoot grass (*Dactyloctenium aegyptium* (L.) Willd.), goose grass (*Eleusine indica* (L.) Gaertn.), and Chinese sprangletop (*Leptochloa chinensis* (L.) Nees) to bispyribac sodium has also been documented (Matloob et al., 2015a). This chemical is marketed under different trade names for broad-spectrum weed control in rice. Being an ALS (acetolactate synthase) inhibitor, chances of resistance evolution are higher as the evolution of resistance towards herbicides of this group has been more frequently documented than the others (Chauhan et al., 2012a). The repeated use of this herbicide might evolve resistance in weed biotypes.

Fenoxaprop *p*-ethyl has been used for weed control in wheat fields for more than 25 years in Pakistan (Jabbar and Mallick, 1994). In the last few years, poor control of *P. minor* was recorded in wheat fields sprayed with fenoxaprop. Recently, Abbas et al. (2017b) based on their preliminary bioassay studies reported Group A/1 resistant *P. minor* in Pakistan. These authors found a high level of resistance against fenoxaprop p-ethyl (ACCase inhibitor) in *P. minor* collected from rice-wheat cropping systems of Punjab, Pakistan. The resistant accessions also showed low-level cross resistance (two-fold) to clodinafop (Abbas, unpublished data). Nevertheless, these findings remain speculative until augmented by much focused work unraveling mechanisms conducive to resistance evolution, genetic studies and differences in fitness or competitiveness between suspected resistance and susceptible weed biotypes. The paucity of new/novel herbicide MOA (mode of action) discovery since last 20 years has deterred weed control and prompted herbicide resistance. More scientific studies should be undertaken in Pakistan to validate the herbicide resistance biotypes of major weeds of important crops. Early confirmation of herbicide resistance and control of resistant biotypes using alternative herbicides/methods is crucial for sustainable crop production in the country. Advocating this issue, Nawaz and Farooq (2016) urged the need to address the resistant biotypes as an integral component of weed management programs in conservation agriculture. Besides this, resistance mechanisms of weed biotypes against commercial herbicides also need to be explored.

2.2. Invasive weeds

Invasive plant species continue to expand in number and geographic range; thus, escalating threats to managed and natural ecosystems (Qureshi et al., 2014). The introduction of alien invasive weed species is one of the burning issues that require immediate attention and remedies (Nasim and Shabbir, 2012; Bajwa et al., 2016). Human activities have resulted in niche provision to invasive plant species to invade natural and managed ecosystems in Pakistan (Riaz and Javaid, 2009; Khan et al., 2011, Marwat et al., 2010). List of invasive plants of Pakistan is given in Table 2. These plants include purposefully introduced tree species like *Ailanthus altissima*, *Broussonetia papyrifera, Eucalyptus camaldulensis* and *Robinia pseudoacacia* that later become aggressive by suppressing or replacing local vegetation. Besides the terrestrial weeds, *Alternanthera philoxeroides* (Mart.) Griseb., *Eichhornia crassipes* (Mart.) Solms and *Salvinia molesta* Mitchell have been reported as major invasive weeds of aquatic habitats (Abbas et al., 2014; Rashid et al., 2014). The relative proportion of different plant categories in the invasive flora of Pakistan is shown in Fig. 2.

Factors like lack of natural predators, habitat degradation, adaptive nature of alien environments, inherited plant attributes for rapid growth, high seed output, diverse seed dispersal modes, phenotypic plasticity, genetic diversity, resistance to various environmental stresses, staggered seed dormancy and allelopathic nature has favored the invasion potential of these weed species in Pakistan (Marwat et al., 2010; Ali et al., 2011, 2012; Nasim and Shabbir, 2012; Rashid et al., 2014; Munawar et al., 2015). These weeds pose threat to abundance and diversity of local flora and fauna, adversely effecting ecosystem functioning (Khan et al., 2011; Bajwa et al., 2016). Ziska et al. (2011) postulated that rise in atmospheric CO_2 concentration can have a profound effect on the biological processes of alien invasive weed species aiding to their invasion potential. For example, these authors reported a 70% increase in the growth of *C. arvense*, an invasive perennial C_3 weed species. This weed is also common in Pakistan (Nasim and Shabbir, 2012) and its infestation is increasing day by day.

P. hysterphorus is also one of the worst invasive weeds (Tanveer et al., 2015b) that has invaded both managed and natural ecosystems in Pakistan causing enormous loss of fodder production, biodiversity, maize yields, and allergy in mammals (Shabbir and Bajwa, 2006; Javaid et al., 2007; Hanif et al., 2012; Khan et al., 2012a; Safdar et al., 2015).

Table 2
List of highly invasive species reported in Pakistan.

Invasive species	Family	Life form	References
Ailanthus altissima (Mill.) Swingle	Simaroubaceae	Tree	Hussain (2003) Khan et al. (2009)
Alternanthera pungens Kunth.	Amaranthaceae	Herb	Marwat et al. (2010)
Amaranthus hybridus L.	Amaranthaceae	Herb	
Amaranthus viridis L.			Khan et al. (2011)
Asphodelus tenuifolius Cav.	Liliaceae	Herb	Nasim and Shabbir (2012)
Avena fatua L.,	Poaceae	Grass	
Broussonetia papyrifera (L.) Vent.	Moraceae	Tree	Qureshi et al. (2014)
Cannabis sativa L.	Cannabaceae	Herb	Bajwa et al. (2016)
Carthamus oxyacantha M. Bieb.	Asteraceae	Herb	Ali et al. (2017b)
Conyza bonariensis (L.) Cronquist	Asteraceae	Herb	
Emex spinosus (L.) Campd.	Asteraceae	Herb	
Eucalyptus camaldulensis Dehnh.	Polygonaceae	Herb	
Galium aparine L.	Rubiaceae	Herb	
Imperata cylindrica (L.) Beauv.	Poaceae	Grass	
Ipomoea eriocarpa R. Brown,	Convolvulaceae	Herb	
Lantana camara L.	Verbenaceae	Shrub	
Monochoria hastata (L.) Solms	Pontederiaceae	Herb	
Parthenium hysterophorus L.	Asteraceae	Herb	
Phragmites austrailis (Cav.) Trin. ex Steud.	Poaceae	Grass	
Pistia stratiotes L.	Araceae	Herb	
Prosopis juliflora (Sw.) Dc.	Fabaceae	Shrub	
Robinia pseudoacacia L.	Fabaceae	Tree	
Silybum marianum (L.) Gaertn.	Asteraceae	Herb	
Tagetes minuta L.	Asteraceae	Herb	
Trianthema portulacastrum L.	Aizoaceae	Herb	
Xanthium strumarium L.	Asteraceae	Herb	

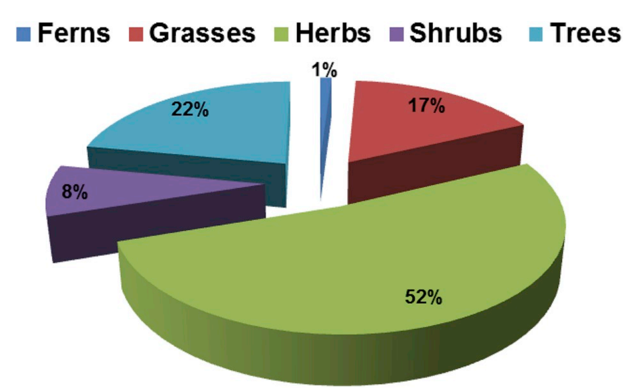

Fig. 2. Relative proportion of different plant categories in invasive flora of Pakistan (Qureshi et al., 2014).

Shabbir (2012) using CLIMEX model predicted increased invasion of this weed in Pakistan under a changing climate scenario (+3.0 °C). Applying irrigation scenarios (summer 1 mm day^{-1}, and winter 0.5 mm day^{-1}) to CLIMEX simulated greater invasion potential in the Southern regions of Pakistan where monsoon showers (causing frequent flooding of Indus River Basin), and canal water irrigation result in extra moisture availability. Recently, Jabeen et al. (2015) investigated the genetic structure of 11 Pakistani populations of *P. hysterphorus* including two populations from Australia using ISSR finger printing. About 18% diversity was found among populations and 82% within the populations. Compared to Australian counterparts, genetic diversity was highest amongst Pakistani *Parthenium* populations, while, gene flow was limited. These authors acknowledged the genetic heterogeneity as one of the main factors responsible for the invasive potential of this weed. Adding further, such heterogeneity among populations was attributed to the multiple introductions.

Studies documenting the influence of alien invasive weeds on biodiversity and agricultural production are scanty in Pakistan (Khan et al., 2011). No regional catalogue depicting information on invasive species is available (Qureshi et al., 2014). Focused research is needed to unravel mechanisms and vulnerabilities conducive to the success of alien invasive weeds, their monitoring, early detection and warning systems, development of regional databases, strengthening the legislative, quarantine and management systems. Assessment of ecological and economic impacts and improving public awareness also remain germane issues to be addressed. Climatic niche shifts, geographic distribution, introduction and dispersal pathways, and range and host shifts of invasive plants also need to be explicitly studied. Environmental and economic impact of neglecting these aspects can be substantial. This is particularly important in the backdrop of anticipated increase in international trade in near future through China-Pakistan Economic Corridor. Increased trade globalization is a major route by which new plant species capable of bringing large-scale ecological change are introduced in a particular non-native region. It is worthwhile to mention the acute shortage of trained weed science faculty and typical courses aiming to improve the invasive plant management in Pakistan.

2.3. Climate change and weeds

Most of the recent work on climate change in Pakistan focus on decision support systems and crop modeling to simulate crop growth and yield under present and future climatic scenarios. Climate change impact on weeds as an ineviTable companion and botanical pest of crops largely remained eschewed in Pakistan. Lack of precise information on the effect of climate change on agricultural pests particularly the weeds remains a major impediment in portraying the true picture of this issue (Ramesh et al., 2017). Nevertheless, the substantial environmental, ecological impacts and economic costs warrant the need to unravel these interactions on a priority basis (Ziska and McConnell, 2015). If the present trend of rising in atmospheric CO_2 continues, it is expected to reach 600 ppm with a concurrent rise in atmospheric temperature to the tune of 1.5–4.5 °C by the middle of 21st century. No local study that quantified the response of crop and weeds to CO_2 in competitive environments is available. Therefore, there is an urgency to appraise this effect in competition with a mixture of weeds and crops.

Further, the impact of climate change on the geographical distribution of weeds in managed ecosystems also needs attention. Changes in the floristic composition of weed communities in response to crop establishment methods, alternate moisture and tillage regimes, and other cultural practices are copious in the literature. Albeit, studies focusing exclusively on changes in weed communities in the backdrop of elevated CO_2 and its interaction with other climatic variables (temperature, rainfall etc.) are scanty although this could affect over all structure and function of crop field ecosystems. Weeds once considered as minor could become highly relevant due to range shift in the climate change scenario.

There is a growing body of consensus that suggest a decrease in herbicide efficacy at a higher CO_2 concentration (Ziska and Teasdale, 2000; Ziska et al., 2004). This implies an overall decrease in herbicide efficacy due to a dilution effect, rendering available herbicide options less effective, and more herbicide input for the same level of weed control that is realized today. Under such scenario, perennial weeds are expected to become more problematic, and difficult to control even with glyphosate. There is no consensus over the future rainfall prediction, except that it would become erratic, and consequently, floods and droughts would become recurrent phenomena. Prolonged drought spells will favor C_4 and parasitic weeds like *Striga hermonthica* (Delile) Benth. Contrarily, under increased moisture availability, weeds like *Rhamphicarpa fistulosa* (Hochst.) Benth. would thrive better. Switch to rice direct seeding from transplanting in quest of water saving has already increased weed competition, and altered weed dynamics (Matloob et al., 2015a,b). The increase in herbicide volatilization is anticipated in the wake of an increase in aridity and drought. On the other hand, frequent rain showers will limit the “rain safe periods” available for herbicide application besides promoting leaching of soil applied herbicides and triggering subsequent ground water contamination (Ramesh et al., 2017).

Climate change has led to the altered distribution of weeds, for example, the appearance of *Marsilea* sp. and *Alternanthera* sp. under wetter conditions in rice in Pakistan. The water scarcity is driving the switch to DSR, promoting recalcitrant grass weeds like *D. aegyptium*, *E. indica*, *L. chinensis* and weedy rice (*Oryza sativa* f. spontanea) in aerobic rice (Matloob et al., 2015a; Ramesh et al., 2017). The infestation of *P. minor* is expected to worsen in wheat fields against anticipated rise in CO_2. This weed had also evolved resistance against isoproturon and fenoxaprop in the Indo-Gangetic Plains. Hence, chemical control of this weed will be difficult in near future. Similarly, weedy rice will be more problematic in cultivated rice fields. In crux, this reflects the potential of increased weed pressure and subsequent competition in rice-wheat cropping system of the Pakistan.

Despite several short-term bioassay studies, research efforts to envisage weed biology and ecology in the backdrop of climate change, especially under long term system-level experiments continue at a slow pace. Such research is not only complex and long term, but it also requires an inter-disciplinary approach.

2.4. Herbicide-tolerant crops

The advent of herbicide-tolerant crops can dramatically change weed management scenario in the cropping systems (Rizwan et al., 2015). Herbicide (glyphosate) tolerant crops have not yet been introduced for general cultivation in Pakistan. However, research efforts are underway to develop herbicide tolerant sugarcane (Nasir et al., 2014), cotton (Latif et al., 2015) and lentil (Rizwan et al., 2017). Worldwide, crop-related weed species is an issue in introducing herbicide-tolerant crops, for example, weedy rice (*O. sativa* f. spontanea) in DSR, jointed goatgrass (*Aegilops A. cylindrica*) and quack grass [*Eltrygia repens* (L.) Gould] in wheat, cruciferous weeds in rapeseed, wild sunflower in sunflower crop, johnson *grass* [*Sorghum halepense* (L.) Pers.] and shattercane (*S. bicolor*) in sorghum. Worldwide, weedy rice has now become a major issue in rice production systems, reducing rice harvest by the 30–50% in the United States alone (Shivrain et al., 2009). Apprehensions associated with herbicide-resistant crops such as gene transfer between wild relatives particularly in the center of crop origin, negative development of super weeds, impacts on biodiversity, and health issues (Rao, 2014; Hassan et al., 2016) warrant the need for educational and awareness activities while taking on board public groups, stakeholders, and policy makers to foster adoption process particularly in the country. Biotech seed industry should devise play safe mechanisms of herbicide-tolerant crop development to avoid gene introgression to related weeds. Transgenic herbicide tolerant crops can also be a step ahead towards the management of parasitic weeds.

2.5. Parasitic weeds

Parasitic weeds pose a serious threat to the productivity of fodder, legumes, orchards and cash crops like tobacco in Pakistan. About 54 parasitic weed species have been reported to infest economically important crops and trees in Pakistan (Mukhtar et al., 2012; Iqbal et al., 2014). Rainfed and low input systems are particularly vulnerable to the infestation of parasitic weeds. Increasing problems of parasitic weeds (e.g., *Striga* sp., *Cuscuta* sp., *and Orobanche* sp.) under continuous cultivation of host crops (e.g., maize, sorghum, sugarcane, rice, lucerne, berseem, legumes, millets, tobacco, and vegetables) combined with low soil fertility have been observed. These weeds are expected to extend their geographic range under predicted climate change affecting the productivity of rainfed and low input cropping systems (Rodenburg et al., 2011; Ramesh et al., 2017). Athar et al. (2007) reported that Orobanchaceae was the dominant family of parasitic weeds in Pakistan with 25 plant species followed by Cuscutaceae (17 plant species). Infestation of *Orobanche* as root parasite of tobacco has been found in all the major tobacco growing regions in the provinces of Punjab (Ashiq and Aslam, 2014) and Khyber Pakhtunkhwa (Khan et al., 2004a). Under the threat of these parasitic weeds, many farmers have abandoned crop cultivation and cleared their orchards. Due to their close association with the host root, concealed underground plant parts during most of the lifecycle, prolific seed production with seed viability for more than 15 years in soil, parasitic weeds, such as *Orobanche* and *Striga* are difficult to control (Aly and Dubey, 2014). Developing robust, cost effective and reliable management options for parasitic weeds would be a significant contribution towards agriculture development in the Pakistan.

2.6. Conservation agriculture and weeds

As the tillage intensity is minimized, weed management can become a limiting factor in crop production. Some other common problems under conservation include early seedling emergence from recently produced weed seeds that remain near the soil surface, lack of disruption of perennial weed roots, interception of herbicides by thick surface residues, and change in timing of weed emergence (Matloob et al., 2015a,b). Adoption of conservation tillage practices have provoked weed flora shifts from annual to perennial, and difficult-to-control weeds in the rice-wheat cropping systems of Pakistan (Matloob et al., 2015a,b; Nawaz and Farooq, 2016). Adoption of rice direct seeding as an alternative to puddled transplanted rice (PTR) has changed weed spectrum as well pressure. Weeds traditionally not found in rice fields like *T. portulacastrum* have become dominant in such systems (Farooq et al., 2011a; Matloob et al., 2015a). Khaliq et al. (2010) reported that direct seeded rice crop grown under conventional tillage (CONT) practices in Pakistan was initially taken over by *T. portulacastrum*, while the grasses such as *Echinochloa* spp., *D. aegyptium*, and *E. indica*, and sedges (*Cyperus rotundus* L. and *C. iria* L.) were competitive throughout the growing season. Likewise, direct seeded rice crop established under zero tillage (ZT) was dominated by *D. aegyptium* as a major grass weed (Matloob, 2014). He undertook several studies and found that CONT favored broad-leaved weeds viz. *T. portulacastrum*, while ZT favor grasses (especially *D. aegyptium*). He also reported the tolerance of weeds like *C. rotundus* and *D. aegyptium* to the application of pre- (pendimethalin) and post-emergence (bispyribac sodium) herbicides in Pakistan. Farooq and Nawaz (2014) recorded significantly lowest density of *Chenopdium album* L. when wheat was grown on the field vacated by PTR. Nevertheless, densities of *P. minor* and *Rumex dentatus* L. were lower in the case of rice direct seeding. Accruing interest in conservation agriculture warrants the need to assess weed and crop behavior, and their association patterns as influenced by various management practices under such system. Changes in weed spectrum over time under conservation agriculture need to be regularly monitored for sustainable weed management and overall system productivity. Moreover, improvement and fine tuning of agricultural machinery keeping in view the farmer's feedback, soil types and cropping systems also need attention of researchers.

2.7. Weed science or science of herbicides

Weed research is mistakenly understood as simple field herbicide testing in Pakistan. Although in true essence, discipline has roots in weed ecology and biology. With the increased availability of selective herbicides for weed control, ecologically sustainable weed management as an integral component of cropping systems seems neglected. In Pakistan, herbicide usage accounted for 14% of the total pesticide consumption (Khan, 1998), which now has increased to 23% (Fig. 3) estimated at 30–32 billion PKR ($300 Million Approx.). The area being sprayed with herbicides has expanded to 993 thousand hectares in Pakistan (ACO, 2010). Although herbicides have revolutionized agricultural production in Pakistan with significant yield improvements (Salarzai et al., 1999; Aslam, 2016), yet, continuous use and reliance on herbicides has resulted in weed flora shifts, evolution of resistant weed biotypes, off-site movement of herbicides in agro-ecosystems and contamination of surface and ground water (Matloob, 2009; Matloob et al., 2015a; Aslam et al., 2017). The herbicide use is increasingly constrained by the increase ecological and health issues, and public awareness. The design of weed management systems with reduced reliance on herbicides seems imperative against the backdrop of herbicide related problems.

Weed science as a discipline has been criticized as "science of herbicides" rather than the science of weeds (Zimdahl, 1991; Harker and O'Donovan, 2013). Harker and O'Donovan (2013) examined the weed science publications from 1995 to 2005 and found that publications in weed science were higher on chemical control rather than on an integrated approach. Same is true for Pakistan. A number of papers describing herbicide efficacy outnumber those dealing with weed ecology, economic threshold levels, seed bank dynamics, IWM and the fate of applied herbicide in the biosphere. A voluminous body of scientific literature is available either on herbicides performance or their interaction with other cultural practices in various crops and cropping systems of Pakistan. Nevertheless, lack of papers focusing on public health safety, education and the training, economics, off-target damage, ethical issues, and policy perspective regarding weeds and conveying scientific views about these subjects suggest these issues are not on the top priority list of Pakistani weed scientists.

2.8. Lack of trained weed scientists, and neglected areas of research

Herbicide residues in crop produce, soil, and subsequent contamination of surface and ground water are the areas of concern that require immediate attention (Sondhia, 2008). Besides contaminating soil and water, some herbicides interfere with soil enzymatic and microbial functions thereby adversely affecting many reactions and transformations regulating soil health (Hussain et al., 2009). These research areas have seldom been addressed as these require a high level of

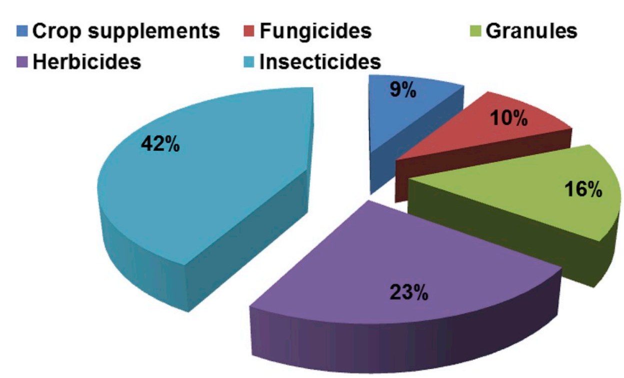

Fig. 3. Crop protection market of Pakistan (Anonymous, 2017).

expertise and sophisticated instruments. Usually, scientists working on such aspects are from other closely related disciplines and have limited background knowledge of weed science. Contrary to entomology, and plant pathology, there are no or very few departments devoted solely to weed science in agricultural universities in Pakistan. Moreover, there is little or no faculty assigned to fruit orchards, ornamentals, aquatic, forest and pasture weed control in universities. Number of research scientists devoted to non-cropland weed management, turf, vegetables, ecology, and statistical issues pertaining to weed science is also limited. Moreover, different degree awarding institutes located at different places in a country have almost homogenous weed science curricula that do not consider regional variations related to weed species, management practices, crops and cropping sequences, input levels, socio-economic background, and weed management skills of farmers.

2.9. Fault lines in herbicide registration, and application

Weeds, unlike other crop pests, go unnoticed as damage is not apparent during the early growth stage. Famers do not perceive the extent of weed related problems until things go from bad to worse. The herbicide related constraints in Pakistan include (a) inadequate knowledge of herbicide selection under a given set of agro-ecological conditions, (b) neglecting the previous field history and target weed flora, (c) poor timing of application, (d) use of wrong nozzle, (e) under or over dose of product resulting either in poor weed control or toxicity to the main crop, (f) tank mixing incompatible products (g) spraying using unfit water as a carrier, (h) spraying without calibration and (i) repeated use of herbicide/s with same mode of action. Most of the currently available herbicides have a narrow spectrum and target few weed species, and seldom provide season-long weed control (Khaliq et al., 2013, 2014). Moreover, many herbicides registered for rice require critical water regimes and flooding depths to be effective. Soil moisture and tilth play an important role in herbicide efficacy, as most pre-emergence herbicides fail to control weeds when the soil is dry (Yaseen et al., 2015).

The efficacy of herbicide depends on many factors as soil type, organic matter, moisture content, prevailing temperature, etc. (Qasem, 2011; Matloob et al., 2015). Moreover, crop sequence under different agro-ecological conditions also varies to a large extent. All this warrants the local test and trials of any herbicide before it is registered and approved for general use by farming community. There is no harm in allowing the registration of pesticides on Form-17 because such herbicides are already under use in developed countries and safe from the environmental point of view. This is the shortest way to introduce and benefit from herbicides with new chemistry. Multinational companies usually introduce herbicides through Form-17 after 2–3 years in house trials. However, the companies may be advised to involve research personnel from universities and public sector organizations to strengthen the validation of their in house trials.

Another point that needs emphases is establishing the validity and confirmation of active ingredient (a.i) in herbicide formulations. Quite often, the formulation does not contain a proper dose of a.i as indicated on the label that inferences the efficacy of the herbicide enormously. In the registration process, a strict mechanism should be laid out for testing a.i as per label.

The introduction of ever new grades with different concentration/s of same active ingredient under different trade name/s of the same herbicide also necessitates its extensive testing before these are registered. And at last, but by no means least is the environmental impact of any farm chemical that should stand at first priority even more than its efficacy. The generic comparison should be restricted to carry out in-house trials before they get their samples of herbicides approved as per Form-17. They should in no way be allowed to market the herbicides before such trials.

2.10. Weed science education and extension

Professional competency of weed scientists and agricultural extension staff is crucial regarding weed menace and its realization for effective management by the farmers. Khan et al. (2012b) carried out a survey to appraise the professional capabilities of agricultural officers (the main source of information to farmers) regarding weed science. The result revealed significant differences for professional capabilities and only 19% of the respondents had required knowledge pertaining to weeds and weed management. These authors concluded that extension agents were not properly trained to tackle weed related problems of farmers showing incompetency on their parts. The majority of the Pakistani farmers are illiterate and very few of them have access to print and electronic media. Lack of education and training of farmers has been recognized as a key factor of low agricultural productivity (Masood et al., 2012). Ahmad et al. (1988) employed Probit Analysis to estimate that famers contact with extension agents was the most significant variable regarding weed control in wheat. Thus, the role of agriculture extension becomes even more important. Proper in-service training and education of extension personnel's seem ineviTable in this regard.

A strong private-public partnership is vital for fostering this nexus and delivering a set of inputs, services, and guidance for improved weed management. The permanent link between weed researchers and extension staff is direly needed to disseminate innovations to the farming community. It was only this year that weeds were considered as a serious biological constraint to crop production and under the initiative of Punjab Government, a full fledge weed eradication campaign was launched throughout the Punjab with the active involvement of all the stake holders ranging from research and teaching institutes, extension department, farmers, pesticide companies.

Out of approximately 20° awarding institutes offering four years bachelor program in agriculture in Pakistan, no agricultural university except for the University of Agriculture, Peshawar has separate Department of Weed Science. Weed science as a discipline is lagging far behind than other sister disciplines under the umbrella of plant protection like entomology and plant pathology. To harness the real impact of weed science, education and extension system needs to be reoriented. An interdisciplinary (biological science, computer science, engineering, economics, and sociology) collaboration and training of weed scientists can help solve complex weed management challenges of the 21st century. There is a need to develop interdisciplinary programs in weed science to learn more about the complexity of weeds in farming systems and discover and implement new solutions. New curricula in weed science should be focused on the concept of the role of genetics, molecular biology, and biochemistry in weed science. Degree programs in weed science programs with more diverse curricula focusing on locally important weed issues besides fundamental concepts at classroom, laboratory and field levels will foster students' ability to tackle complex situations by enhancing critical thinking and site-specific weed management. Capacity building, allocation, and mobilization of more resources and funding for weed research and education are essential in handling the frontier and emerging issues of weed science in Pakistan. The number of positions devoted to weed science research, teaching, and extension needs to be increased since acute shortage is felt in some instances especially when it comes to natural ecosystems and non-cropland weeds, and invasive plant management. Like other plant protection disciplines (plant pathology, and agricultural entomology), weed science should also be a major department of all agricultural universities offering graduate- and post-graduate degree programs. Regional weed research institutes need to be established in distinct cropping/agro-ecological zones of Pakistan to undertake location specific and strategic research. Recently, Aslam (2016) proposed improvements in agriculture education-training-research-extension nexus to upscale agricultural production in Pakistan.

3. Weed management in important crops

3.1. Wheat

Weed infestation is one of the main causes of low wheat yield in Pakistan (Marwat et al., 2011). Khan and Haq (2002) reported that a mixed stand of narrow and broad-leaved weeds can cause 48% yield reductions in wheat. The major weeds of wheat in Pakistan causing huge economic losses are canary grass (*P. minor*), wild oat (*A. fatua*) and lambsquarters (*C. album*). The weeds with relatively less economic importance include wild medic (*Medicago polymorpha* L.), field bindweed (*Convolvulus arvensis* L.), blue pimpernel (*Anagallis arvensis* L.), fumitory (*Fumaria indica* L.), broadleaf dock (*R. dentatus*) and swinecress (*Coronopus didymus* L.). Proper weed management is expected to increase wheat yield by more than one million ton in Pakistan (Marwat et al., 2011).

With the advent of modern drills that enable wheat sowing in rice residues without land preparation, the ZT has emerged as the most promising resource conservation technology in rice-wheat cropping systems (Erenstein and Laxmi, 2008; Nawaz and Farooq, 2016). Under ZT, several authors reported less weed density in wheat crop than conventional tillage (Mann et al., 2008; Usman et al., 2012). However, annual grasses and perennial weed density increases in subsequent years (Nawaz and Farooq, 2016) making available herbicide options redundant. Besides having implications for weed growth, zero tillage can affect herbicide efficacy due to retention by surface residues (Kumar and Goh, 2000). This aspect is seldom considered in most of the local studies available. In the rainfed areas, the wheat crop is already under water stress, the presence of competitive weeds like *C. oxycantha* further aggravates this situation. Weed problems in wheat are getting from bad to worst even in crop sown under irrigated conditions. Many methods such as cultural, mechanical, chemical and biological can be used to control weeds in wheat. Nevertheless, manual weeding is not feasible as it is slow, cumbersome, time consuming and very laborious. The cropping intensity and labor charges are ever increasing so that weed control with traditional methods such as *Dab* (stale seedbed or suicidal germination) and hand weeding, respectively has become impossible. In the rice-wheat system, very few farmers practice crop rotation as a weed management tool (Narwal, 2000). Most of the weeds can also be suppressed by cover crops; however, the grain yield of the main crop is reduced up to 30% due to competition with weeds (Chikoye et al., 2002). Moreover, in the irrigated areas of Pakistan wheat is sown mostly by broadcasting seeds which make weeding even difficult (Byerlee et al., 1986). Line sowing using drills could facilitate weed control and subsequent inter-culture. Mechanical weed control is weather dependent and fragmentation of perennial weeds by cultivation further aggravates their spread. This scenario has led to over reliance on herbicides as sole mean of weed control in wheat (Matloob, 2009). It is unequivocal that over dependence, repeated and indiscriminate use of herbicides with a similar mode of action has given rise to resistant biotypes, population shifts and increase in weed seed banks.

3.2. Cotton

The cotton crop is seriously infested with grasses, sedges, and broadleaf weeds that can cause more than 30% reduction in cotton yield (Jabran, 2016). The weeds that are considered most serious in cotton crop in Pakistan are *C. rotundus, Cynodon dactylon* (L.) Pers.*, Dicanthium annulatum* (Forssk.) Stapf.*, Sporobolus clandestinus* (Biehler) A.S. Hitchc. and *T. portulacastrum* (Rajput et al., 2008). Being a wide-rowed important cash crop of the country, farmers use intensive weed control in cotton by the chemical and mechanical means. Two herbicides viz., S-metolachlor and pendimethalin are mostly used in Pakistan as a pre-emergence application for controlling weeds in cotton. However, S-metolachlor 960 EC at 2.5 L ha^{-1} gave efficient (93.81%) weed control and the highest seed cotton yields (2395 kg ha^{-1}) (Jarwar et al., 2005).

However, there is a need to test some other cost-effective weed management strategies that give long-term, sustained and eco-friendly weed control. A few studies in this regard proved that aqueous extracts of allelopathic plants [sorghum (*Sorghum bicolor* L. Moench) and brassica (*Brassica napus* L.)] in combination with herbicides could help farmers in reducing herbicide doses, a step towards environment safety (Iqbal et al., 2009, 2014). Ahmad et al. (2015) found that soil solarization using black plastic mulch was an effective weed management strategy in cotton. In addition to weed control, it also enhanced water use efficiency and cotton yield by minimizing evaporation losses from the soil surface. Integration of all possible weed control methods provides most efficient, long-term weed control along with good quality produce of cotton (Jabran, 2016). The best weed control in cotton along with highest cotton yield was obtained by applying S-metolachlor herbicide in combination with manual hoeing (Tanveer et al., 2003). Similarly, Ali et al. (2013a) found that pre-emergence application of pendimethalin along with inter-culturing and hand-weeding is more effective and efficient weed management strategy for higher yield in flat-sown cotton.

3.3. Rice

There are two contrasting methods of rice cultivation in the country: the conventional PTR method and direct seeded rice (DSR) technique. More than 90% of the rice is cultivated under the conventional sowing system (Matloob et al., 2015) which involves flooding the field before land preparation and transplanting 30–35 days old rice seedlings manually or mechanically under puddled conditions (Khaliq et al., 2011; Ali et al., 2014). Despite its advantages of low weed infestation, the traditional method of PTR is becoming non-popular among growers due to its intensive labor and water input requirements (Farooq et al., 2009; Khaliq et al., 2011) under the current scenario of water and labor shortage in Pakistan (Mann et al., 2007). A recent survey showed that farmers of Punjab are interested in adopting DSR technology (Awan et al., 2015). The DSR involves sowing seeds on a finely tilled seedbed either manually or with a tractor-drawn drill. Time, labor, water and energy savings are the benefits of DSR (Khaliq et al., 2011; Chauhan, 2012).

Due to favorable growing conditions, rice crop is usually suffered from a more prolific weed infestation compared to other crops. Moreover, the type of weed flora and expected yield losses in PTR vary greatly from those observed in DSR. The usual grain yield losses in PTR range between 15 and 20% that may exceed 50% under severe weed infestation, depending upon weed type and intensity (Anonymous, 2003). The most common weeds in this system are *E. crus-galli, E. Colona, E. glabrescens, Cyperus difformis* L.*, C. rotundus, C. irria, Bolboschoenus maritimus* (L.) Palla.*, E. indica, Paspalum distichum* L., and *Marsilea minuta* L. (Ahmad et al., 2004). On the other side, the grain yield losses in DSR production system vary from 48 to 80% and major weeds are *C. rotundus, C. iria, C. difformis, Sphenoclea zeylanica* Gaertn.*, E. colona, E. crusgalli.*, *Eclipta prostrata* (L.) L.*, T. potulacastrum, D. aegyptium and Portulaca oleracea* L. (Mann et al., 2007; Hussain et al., 2008).

Regarding weed control, farmers use pre-emergence herbicides (acetochlor, butachlor, oxadiargyl, penoxsulam, ethoxysulfuron ethyl, pyrazosulfuron) in PTR. A good weed management is possible in conventional cultivation system of PTR due to a wide choice of pre-emergence herbicides available in the country that gives absolute control of all types of weed flora (Ashraf et al., 2006). However in the case of DSR, very few selective post-emergence herbicides (bispyribac sodium either alone or in combination with bensulfuron methyl) are available in the market that is not so much effective against some weeds (Mann et al., 2007). That is why weed control in DSR remains a challenging task for DSR growers and is a major hurdle in the widespread adoption of this new rice cultivation technique in Pakistan.

3.4. Maize

Major weeds infesting the maize crop are *C. dactylon, C. rotundus, D. aegyptium, T. portulacastrum, S. halepense, Digera arvensis* Forssk., and *E colona* (Riaz et al., 2007; Khatam et al., 2013). Grain yield losses due to mixed weed flora in maize ranged from 35 to 50% (Maqsood et al., 1999; Maqbool et al., 2006). However, sole infestation of *P. hysterophorus,* a newly emerging invasive weed may cause reduction up to 50% in maize grain yield (Safdar et al., 2015). Under agro-ecological conditions of Punjab-Pakistan, the economic threshold of *P. hysterophorus* in maize is 1.2 plants m^{-2} (Safdar et al., 2015). The weed control in maize should be employed relatively earlier as the critical competition period of weeds in maize commenced from 15 to 21 days after crop emergence (Maqsood et al., 1999; Maqbool et al., 2006). Safdar et al. (2016) suggested that the critical timing of parthenium weed removal to avoid 5% and 10% maize grain yield loss ranged from 8 to 13 and 17–23 days after crop emergence, respectively.

The most commonly used selective herbicides in maize are atrazine, S-metolachlor, nicosulfuron, dicamba, triasulfuron, metribuzin, mesotrione and propisochlor that are used in different formulations and combinations or directed post-emergence application of glyphosate and paraquat.

Herbicide screening studies in maize showed that among various post-emergence herbicides viz., S-metolachlor at 600 mL $acre^{-1}$, propisochlor 40% SE at 600 mL $acre^{-1}$, nicosulfuron 75% WG at 30 g $acre^{-1}$ and atrazine 38% SC at 400 mL $acre^{-1}$, S-metolachlor proved to be the most effective herbicide in terms of better weed control (72.35%) and higher net returns (Rs. 60326 ha^{-1}) (Khatam et al., 2013). Amin et al. (2008) found that among pre-emergence herbicidal applications of pendimethalin 330E at 3.75 L ha^{-1}, S-metolachlor 960 EC at 2 L ha^{-1}, S-metolachlor + atrazine 720SC at 0.98 L ha^{-1}, and atrazine 38SC at 1 L ha^{-1} in maize, S-metolachlor + atrazine showed the highest weed control along with maximum grain yield (2.84 t ha^{-1}). Tank mixed application of herbicides with adjuvants helps in reducing herbicide dose. It has been demonstrated that up to 10% dose of formasulfuron + isoxadifen-ethyl and up to 20% dose of herbicide mesotrion + atrazine could be reduced from their recommended rates by mixing 3% urea solution as an adjuvant in maize (Naveed et al., 2008; Akhter et al., 2017). Selection of weed competitive cultivars of maize is another option for minimizing herbicide dose/s as demonstrated by Hassan et al. (2010).

3.5. Sugarcane

Sugarcane is a long duration crop that is cultivated in two seasons (spring and autumn) in Pakistan. The critical weed crop competition period in sugarcane lies from 90 to 120 days after sowing (Afghan, 1996) that is longer compared to other field crops. However, Zafar et al. (2010) noted that initial 45 days after sowing is the critical period of weed-crop competition period in sugarcane. Therefore, weed control for a longer period is required in this crop.

Weed flora varies in sugarcane crop grown in different provinces of Pakistan. For instance, in Sindh province, the most prevalent and dominant weed species of sugarcane crop are *Desmostachya bipinnata* (L.) Stapf*., C. dactylon, T. portulacastrum, Tribulus terrestris* L*., Alhagi maurorum* Medik*., C. rotundus, D. annulatum, Convovulus arvensis* L. *and Achyranthes aspera* L. (Qureshi, 2004). However, in KPK major weeds of sugarcane fields are *C. dactylon, Brachiaria eruciformis* (Smith) Griseb. and *C. rotundus, S. halepense*, and *Digera muricata* (L.) Mart. are the most abundant weeds (Afridi et al., 2015). The weeds cause losses in sugarcane yield in the range of 20–25% (Khan et al., 2004b). Both mechanical and manual weed control methods are the most common among farmers (Khan and Khan, 2015). However, chemical weed control through pre-emergence application of ametryn + atrazine at 2.5 kg ha^{-1} is mostly used for weed control in sugarcane crop (Qureshi and Afghan, 2005). Akhtar and Ahmed (1999) demonstrated that both the pre-emergence application at planting, and post-emergence application 90 days after planting of atrazine + ametryn at 3.4 kg ha^{-1} gave efficient weed control that resulted in higher cane yields. Less weed burden and increased crop productivity in sugarcane was realized by integrating herbicides (ametryn + trifloxysulfuron at 750 g a.i. ha^{-1}) with mechanical weed control (Zafar et al., 2015).

3.6. Chickpea

Among different legumes, chickpea is an important cool season food legume that is primarily grown on marginal lands with minimal inputs on residual soil moisture in Pakistan. Chickpea is a poor weed competitor (Khaliq et al., 2012) due to its slow growth rate and limited leaf area (Tanveer et al., 2015a). Weed competition is a serious factor conducive to low yields of chickpea. Most of the weeds infesting chickpea fields are annual with high reproductive potential and chickpea fields were found to be infested by 50 weed species belong to 43 genera and 20 distinct families (Hussain et al., 2015). According to Ozair (1987), the yield losses due to weeds in pulses ranged between 75 and 84%. Yield losses of 24–80% have been reported in chickpea due to weeds (Tiwari et al., 2001). In Pakistan, weeds reduced chickpea yield up to 24–63% (Tanveer et al., 1998). The major weeds of chickpea in irrigated area of mix cropping zone of Punjab are *Chenopodium album*, *C. murale*, *Fumaria indica*, *Rumex dentatus*, *Vicia sativa* and *Avena fatua* (Tanveer et al., 1998). In the rainfed areas, important weeds of chickpea are *Medicago ploymorpha* L., *A. arvensis* L., *C. rotundus*, *F. indica*, *C. dactylon*., *Lathyrus aphaca* L., *C. arvensis* and *C. oxycantha* (Rashid et al., 2009). Wild onion (*A. tenuifolius*) and dragon spurge (*Euphorbia dracunculoides* Lam.) are an important component of weed flora in chickpea (Marwat et al., 2004; Tanveer, 2008), especially in the rainfed areas. In the chickpea-chickpea cropping system of the rainfed thal tract, *A. tenuifolius* is the major weed of chickpea that can reduce chickpea yield up to 60% (Sibtain et al., 2015). These authors predicted a yield reduction of 2.5% with an increase of one *A. tenuifolius* plant m^{-2}. Herbicides, as pendimethalin and s-metalochlor, though capable of providing fairly good control of dragon spurge, were phytotoxic to chickpea, causing chlorosis, reducing plant height and root and shoot biomass (Imran et al., 2009) warranting the need for alternative weed control methods for effective early season weed control. Moreover, under rainfed conditions moisture availability at the time of herbicide application is also a critical factor limiting chemical weed control.

4. Prospects

4.1. Cultural practices

Anticipated climatic changes and herbicide resistance evolution will affect future crop production, and weed management approaches in Pakistan. The distribution and competitiveness of weed species will be altered within the plant community with changes in atmospheric CO_2 levels, temperature, and rainfall (Mahajan et al., 2012), herbicide resistance (Rao, 2014), and hermetic effects of herbicides (Nadeem et al., 2016). Such concerns necessitate the optimization of crop management practices which have a significant effect on the growth and proliferation of certain weed species in Pakistan. Table 3 provides a brief overview of various cultural practices on weed growth and crop yield in different crops.

Weed prevention is considered as a preferred method to control weed species in an agroecosystem as the eradication of weed species is far more expensive and require greater resources (Kawakami et al., 2012). Use of clean seeds, proper composting of manure, and cleanliness of farm implements can prevent weed seed dispersal in the field. Entry of grazing animals in weed-free fields after grazing in weed-infested areas should be avoided especially when weeds are mature (Panetta and Roger, 2005). Care at harvesting must be taken to remove the mimic weeds, for example, *P. minor* in wheat and *E. colona* in rice. Use of

Table 3
Effect of various cultural practices on weed growth and crop yield in different crops in Pakistan.

Cultural Practice	Crop	Weeds controlled	Weed control (%)	Yield increase (%)	Reference
Stale seedbed	Wheat	*A. fatua, P. minor,* and *C. album*	29	5	Safdar et al. (2011)
Stale seedbed + double seed rate	Wheat	Mixed weed flora	60	24	Jabran et al. (2012)
Zero tillage	Wheat	Mixed weed flora	21	16	Areeb et al. (2016)
Narrow row spacing	Wheat	Mixed weed flora	34	19	Areeb et al. (2016)
			57	29	Shah et al. (2005)
			97	13	Abbas et al. (2009)
	Rice	*T. portulacastrum, P. oleracea., A. philoxeroides, D. aegyptium, E. indica, E. colona, E. crus-galli, L. chinensis, C. dactylon, C. rotundus* L. and *C.iria*	24–27	29	Khaliq et al. (2014)
	Sugarcane	*C. dactylon, S. halepense, C. rotundus* and *D. arvensis*	17	−16	Munsif et al. (2015)
Mechanical harrowing	Wheat	*P. minor, A. fatua, C. rotundus, A. arvensis* and *C. album.*	85	39	Khan et al. (2000)
Increased seed rate	Wheat	*S. marianum*	25–27	7–9	Khan and Marwat (2006)
	Rice	*A. philoxeroides, D. aegyptium, E. indica, E. colona,* and *C. rotundus* L.	22–43	66	Khaliq et al. (2012)
Intercropping	Wheat	*Avena fatua, Rumex dentatus*	13–18	18–30	Khan et al. (2013)
	Maize	*C. rotundus*	48–52	−6	Mahmood et al. (2013)
	Cotton	*C. rotundus*	71–97	-8–23	Iqbal et al. (2007)
Early sowing	Rice	*T. portulacastrum, D. aegyptium, E. indica,* and *Cyperus* spp.	63	7	Mubeen et al. (2014)
Late sowing	Wheat	*P. minor, C. album*	42–93	–	Farooq and Cheema (2013)
Sowing method	Wheat	*P. minor, C. album*	20–74	–	Farooq and Cheema (2013)
Weed suppressive cultivars	Wheat	*A. fatua*	–	43	Khan et al. (2010)
Mulching	Maize	*C. rotundus*	75–80	–	Mahmood and Cheema (2004)

cultural practices that may increase the competitive ability of a crop against weeds might also reduce the herbicide load. Features like early vigour, robust growth, deep rooting, and rapid canopy closure provides a competitive advantage to the crops against weeds (Mahajan et al., 2015). Planting density and geometry, row width and orientation, time and method of sowing, frequency and method of irrigation, rate, timing and method of fertilizer application can have a profound effect on crop competitiveness against weeds (Chauhan, 2012; Mahajan et al., 2014; Maqbool et al., 2016). For example, high planting densities suppressed weed biomass by 41–60% with increased rice crop yield (Ahmed et al., 2014).

Crop rotation is one of the most effective strategies for managing weed population in crops. It helps in interrupting the life cycle of weeds, and prevents any specific weed from becoming dominant in the field. The incidence of herbicide resistant *P. minor* was found higher in the rice-wheat rotation compared to the maize-wheat rotation in Pakistan (Abbas et al., 2017b). Shahzad et al. (2016) documented suppressed weed growth in the sorghum-wheat rotation under different tillage systems including zero, conventional, and deep ploughing. Crop rotation also plays a significant role in managing parasitic weeds as they are host-specific plants (Rubiales and Fernández-Aparicio, 2012).

4.2. Hand pulling or hoeing

Hand pulling or hoeing helps to control hardy and herbicide-resistant weeds. The number of weeding and hoeing is decided on the basis of type and extent of the weed problem at various stages, growth patterns, and duration of crop growth, the cost-benefit ratio, and availability of labor (Chatizwa, 1997; Ionescu et al., 1996; Muhammad et al., 2016). For instance, soybean crop needs a weed-free environment for the initial 30 days after sowing (Ionescu et al., 1996). For other crops like peanut and rice, the weed-free fields are required for the first 45 days after sowing/transplanting. Raffaelli et al. (2005) revealed that all the hoeing systems were effectively controlled weeds and increased maize yield as compared to harrowing. Mechanical weed control methods including hand hoe, blade hoe, rice weeder, and conoweeder are as effective as hand weeding. Use of self-propelled and tractor-drawn platforms or flat-bed machine is a recent development in the hand-weeding of row crops. Use of hoeing systems (PTO-powered rotary tiller, precision hoe, and torsion speeder etc.) depends on the type of weeds and crop (Raffaelli et al., 2005). It is necessary to educate farmers in Pakistan about the benefits and use of hoeing, especially advanced mechanical weeders to sustain crop production in the scenario of widespread herbicide resistance in weeds.

4.3. Mulches and soil solarization

Mulches limit the weed growth through restricting sunlight penetration, releasing allelochemicals and physically hindering weeds (Monaco et al., 2002; Abbas et al., 2017c). For weed species, whose seed germination is stimulated by light, mulch application hinders light transmission and subsequently the photosynthesis (Mahajan et al., 2006a). Application of rice, maize, sunflower and sorghum straw mulches ($8\ t\ ha^{-1}$), as a physical barrier, at the time of crop establishment resulted in reduced growth and development of *P. minor* in wheat in Punjab, Pakistan (Abbas et al., 2017c).

Soil solarization as a pre-planting treatment to control soil borne pathogens and weeds was first described in 1976 by Katan in Israel (Katan, 2015). Effective weed control in eggplant nursery was achieved through soil solarization (Mahajan et al., 2006b). The solarization technique, though provided broad spectrum weed control, its use is restricted to regions where the climate is suiTable (intense solar radiation and clear sky), and the land is free of crops for more than a month at the time of mulching (Standifer et al., 1984; Sauerborn et al., 1989). In Pakistan, the use of conventional polyethylene plastic mulches has been restricted to organic farming due to its high cost. Introduction of cheap plastic mulches will increase their use in organic farming and vegetables, especially leafy vegetables, and fruits in which use of herbicides is risky.

4.4. Tillage

Tillage is a principal weed control means, usually adopted to eradicate weeds through the destruction of vegetative and reproductive

organs and accelerate microbial attack ensuring complete weed seed destruction (Monaco et al., 2002). Tillage also has a major effect on the vertical distribution of weed seeds in soil seed bank (Chauhan and Johnson, 2009). In reduced tillage, nearly 40–80% of weed seeds were accumulated in the top 0–5 cm soil layer, resulting in greater weed emergence compared to conventional tillage (Hoffman et al., 1998; Bàrberi et al., 2001). Also, perennial weeds are more likely to establish and become problematic under conservation tillage (Bàrberi et al., 2001; Tuesca et al., 2001). Apart from primary tillage, secondary tillage operations, such as row cultivation and harrowing also influence weed seed banks and species composition. Light harrowing/blind tilling of soil with a blade harrow after sowing of crop or either before the crop plants emerge or while they are in early stages of growth should be practiced in Pakistan. Effect of tillage on weeds might be species specific and depend on the intensity of tillage. Research related to influence tillage on weed ecology, and herbicide efficacy needs to be carried out under different cropping systems.

4.5. Biological control

Weed control through biological agents offers an environmental friendly classical approach, complementing the conventional strategies of weed management (Marwat et al., 2011). Numerous native and non-native organisms have been evaluated to control indigenous and introduced weed species across Asia (Dhileepan and Strathie, 2009; Marwat et al., 2011). Different microorganisms including *Puccinia spegazzinii* de Toni., *Exserohilum monoceras, Puccinia abrupta* Diet. and fungal pathogen ITCC-4896 of *Puccinia abrupta* have been reported to possess herbicidal potential against *Mikania micrantha* Kunth., *E. crus-galli*, *P. hysterophorus* and *L. camara* (Singh, 1989; Thomas et al., 1999; Saxena and Kumar, 2007; Kadir et al., 2008). In Pakistan, not a single myco-herbicide has been registered yet because of several possible biological, technological and commercial constraints in the development of potential myco-herbicides. It was reported that various insect like mealy bug species severely damaged *X. strumarium* and *A. aspera*, two troublesome weeds in wastelands, through feeding on buds, stem surface, and inflorescence (Shafique et al., 2007). In Korean rice fields, *Tanysphyroides* reduced the seed production potential of *Monochoria vaginalis* (Burm.f.) C. Presl ex Kunth. a herbicidal resistance weed, up to 70% (Kwon, 2008).

Classical biological approaches have been practiced in developed countries of temperate regions (Muniappan et al., 2009). Whereas, developing countries in the tropics have not adopted biological control measures. Bio-herbicides have been proposed as an important component of integrated weed management (Kadir et al., 2008). Unfortunately, biological control in Pakistan is still facing several technical and legislative barriers, and its safety and efficacy is questioned.

4.6. Allelopathic approaches

Allelopathic weed control gained considerable attention during the last couple of decades due to associated hazards of chemical weed control (Jabran et al., 2015). The common allelopathic strategies for weed management include use of allelopathic mulches (Abbas et al., 2017c), use of allelopathic cover crops, use of aqueous crop extracts, and residues from allelopathic plants (Ali et al., 2013; Safdar et al., 2016; Abbas et al., 2017a), crop rotation, use of allelopathic cultivars (developed through conventional breeding or biotechnology), intercropping of allelopathic crops with non-allelopathic crops (Farooq et al., 2011b; Jabran et al., 2015). Sorghum mulch significantly reduced the density and dry biomass of *C. rotundus* (Mahmood and Cheema, 2004). A pot study from Pakistan reported that mulches of major field crop including maize, rice, sorghum, and sunflower were effective against *P. minor* (Abbas et al., 2016a). Another study revealed that use of allelopathic mulches of maize, sorghum, sunflower and rice at 8 t ha^{-1} in wheat fields effectively controlled *P. minor* (Abbas et al., 2017c). According to Hong et al. (2003), plants such as *Bidens pilosa* L., *Melia azedarach* L., *Leucaena glauca* Benth., *Tephrosia candida* DC. and *Galactia pendula* Pers. have the potential to be used as allelopathic mulch for weed control in Vietnam and some other Southeast Asian countries.

Allelopathic cover crops may inhibit weeds by physical as well as chemical (allelopathic) effects (Alsaadawi and Dayan, 2009). The aqueous allelopathic extracts of crops such as sorghum, sunflower, mustards, rice etc., have been reported to suppress weeds (e.g. *C. rotundus, C. album, T. partulacastarum,* and *P. minor*) in field crops including canola, wheat, cotton, rice, and maize (Jabran et al., 2008, 2015; Razzaq et al., 2012; Jabran and Farooq, 2013; Doğan et al., 2014; Naeem et al., 2016). Furthermore, inclusion of allelopthic cultivars of crops in rotation (Narwal, 2000; Shahzad et al., 2016) and their intercropping (Chen et al., 2012) can be used to manage weeds. Intercropping of sorghum or sesame in cotton offered an effective control (>70% reduction in fresh and dry weights) of *C. rotundus*, while intercropping of canola in wheat helped suppress weeds such as *P. minor* and *C. album* in Pakistan (Iqbal et al., 2007; Naeem et al., 2012).

4.7. Chemical weed control

Chemical weed control is most effective and widely used weed control method. Use of multiple weed control tactics and judicious use of herbicides is needed for efficient and cost-effective weed control in field crops. Chemical weed control is the backbone of weed management programs in major crops (Jabran, 2016; Singh et al., 2016; Ahmadi et al., 2016). Selection of an appropriate herbicide, its effective dosage, and application timings are critical in attaining satisfactory weed control (Kumar and Ladha, 2011; Chauhan et al., 2012b). Use of herbicides depending on the economic threshold level of a specific weed is crucial to reduce herbicide use (Mehmood et al., 2017).

4.8. Diversification of cropping systems and weed management practices

Generally, diversified cropping systems could be associated with more diversity of weeds as compared to mono-cropping. But, the range of weed diversity will depend on the type of crop involved in the cropping systems and related weed management strategies. For example, more weed diversity was found in the cereal-forage rotation as compared to the cereal-oilseed rotation and cereal monoculture (Stevenson et al., 1997; Légère and Derksen, 2000). Doucet et al. (1999) reported greater influence of weed management practices on weed species composition as compared to crop rotation. Furthermore, low input cropping systems showed more weed diversity than high input system (Bàrberi et al., 1997). Diversified cropping systems and integration of cultural weed control measures with reduced herbicide input needs to be practiced. Importantly, the role of these practices in IWM is required to be re-assessed, to reside the challenge of less immediate financial return than chemical weed control. Optimization and evaluation of such practices under agroecological conditions of Pakistan may help devise robust, resilient and economically viable weed control approaches.

4.9. Weed biology

Understanding biological aspects of weeds can help improve management techniques. Variability in weed germination patterns, and tolerance to extreme weather conditions needs to be explicitly studied especially in countries like Pakistan having more diversified weather and climatic conditions. Investigating the influence of current and anticipated environmental and edaphic factors on the weed seed germination, seedling emergence, growth, reproductive potential and seed dormancy can be useful in predicting floristic composition and weed pressure in near future. Research on weed biology and related management aspects will assist in the development of ecologically-based weed management approaches.

4.10. Improved mechanical equipment

Cultivation practices influence the diversity, seed bank dynamics, seed distribution and dormancy, seedling emergence and survival of weeds. Finger weeders, torsion weeders, and inter-row brush weeders have been introduced to clean and control weed species in the row crops (Van der Weide et al., 2008). These weeders can be tested and optimized for the effective weed control in small- or large-scale farming systems in Pakistan.

4.11. Thermal weed control

Thermal weed control is a technique in which brief exposure of weed foliar parts to high temperatures (100 °C) causes cell membrane damage. This leads to tissue desiccation, and plant usually die within 2–3 days. Flame weeding, soil solarization and use of hot water are some of the possible options. However, these have rarely been used in Pakistan, and need in-depth studies to explore their technical and economic feasibility.

4.12. Capacity building

Due to lack of training about selection and implementation of effective weed control practices, small land holders are unable to cope with the current weed related challenges in crop production (Khan and Khan, 2015). Most of the farmers have very little and superficial knowledge about weed control in general and herbicide use in particular (Hussain et al., 2013). Farmers commonly use a single herbicide without rotation which may lead to resistance development in major weeds (Abbas et al., 2017b). Similarly, the majority of farmers are unaware of selectivity, control spectrum, safety precautions, and potential effects of herbicides on the environment and human health (Sharma et al., 2013). Farmers should be trained to use well rotten farmyard manure in the field to avoid weed seed dispersal. Education of farmers about the impact of non-judicious herbicide usage on the crop, humans, and environment is needed. Creating awareness regarding weed identification, weed biology, cutting-edge innovations, economic threshold levels, herbicide selection and application, and resistance management through trainings and workshops is required to benefit crop production in Pakistan. Farmer-level extension material on diverse topics such as weed identification guides, competition and yield losses due to weeds, crop-specific weed management recommendations, factors affecting herbicide performance, selection, calibration and maintenance of sprayers should be developed keeping in view the local language and illiterate audience.

4.13. Site-specific weed management

Weeds rarely show a uniform distribution in crop fields; however, weed control practices are commonly applied in a blanket approach irrespective of weed distribution (Christensen et al., 2009). This blanket approach increases the herbicide input and decreases efficacy, as herbicide is over or under sprayed across the field without considering spatial and temporal variations in weed population in arable fields. Weed management approaches that target weed plants individually or in patches are more cost-effective and sustainable. The first step towards site specific weed management (SSWM) is identifying and mapping the weeds. Growers can identify weed and its location in the field by using several advanced techniques like ground-based visual estimation to create weed maps, remote sensors (e.g. GreenSeeker ™, N-Sensor ™ and Crop-Circle ™), machine vision weed sensors (the advanced form of sensors that can identify weed in crop based high-resolution images), and soil type to map some weeds directly (Brown and Noble, 2005; López-granados, 2011). The second step is the determination of weed control strategies based on weed identification and distribution pattern (Christensen et al., 2009). The non-chemical SSWM strategies may include the weed cutting for hay purpose, stubble burning around weed patches and increased crop competition through increased seed rate and/or narrow row spacing. In the case of herbicide use, they can be applied by automatic on/off boom spray, adjusting the application rate, and spraying different herbicides to different weed patches. These advanced technologies are not accessible to growers in developed countries (Christensen et al., 2009). In addition to these, the most practical strategies for SSWM in Pakistan are spraying weed patches with a non-selective herbicide (e.g. glyphosate) before they produce viable seeds, cutting of weeds within row crops for hay, and stubble burning around the high density weed patches to destroy seeds.

5. Conclusion

Farmers' awareness and understanding about the economic and environmental impact of weeds are lacking in Pakistan. Multidisciplinary efforts are needed to educate farmers about the negative impact of weeds and convince them to implement effective weed control strategies. Haphazard and indiscriminate herbicide use is alarming due to evolution of herbicide resistance, and potentially harmful impacts of synthetic chemicals on the environment. The existing weed control practices can be integrated in a judicious manner to devise site-specific IWM packages for various cropping systems. Demand-driven research and fact-based learning in weed science will be a step ahead towards sustainable weed management. It is unequivocal that active links between academia-research-industry-extension-farmers will be crucial to frame technological, legislative and policy perspectives of weed management in Pakistan. A comprehensive national weed control program keeping in view the current and anticipated challenges of contemporary agriculture and regional diversity of weed flora is need of the hour to limit weed populations below the economic threshold levels and overcome the monetary losses caused by weeds to the national economy. Establishment of regional weed research institutes in all the provinces of Pakistan is proposed to carry out basic and applied research in weed science.

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